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THESIS

ADAPTIVE, TACTICAL MESH NETWORKING: CONTROL BASE MANET MODEL

by

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September 2010

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13. ABSTRACT (maximum 200 words)

Mobile Ad Hoc Networks (MANET) do not depend on any kind of established infrastructure; therefore, they can be deployed without any need of fixed infrastructure. MANET are expected to play an important role in delivering real-time services to war fighters in tactical military networks by providing infrastructureless communication. The nature of MANET, such as node mobility, unreliable transmission medium and restricted battery power, makes it more challenging for them to deliver the information warfighters need on tactical missions.

As the demand for higher bandwidth real-time tactical services increases, more bandwidth efficient tactical network solutions must be developed. The goal of the CBMANET program was to develop an adaptive networking capability that dramatically improved performance and reduced communication failures in complex communication networks. However, field experiments showed that the proposed network coding for CBMANET was not adequate to leverage the limited network resources to transport time-critical messages and interactive video in varying network conditions. Therefore, CBMANET was evaluated as not usable in supporting the tactical network operations in future IT mobile services with its current coding, but it still can be useful in mobile networks that are not transferring time critical information. CBMANET remains a promising technology in the area of MANET improvements.

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LIST OF ACRONYMS AND ABBREVIATIONS

BSS	BASIC SERVICE SET
C2	COMMAND AND CONTROL
C4I	COMMAND, CONTROL, COMMUNICATIONS, COMPUTERS, AND INTELLIGENCE
CBMANET	CONTROL BASED MOBILE AD HOC NETWORKING
COTS	COMMERCIAL OFF THE SHELF
DARPA	DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
DHS	DEPARTMENT OF HOMELAND SECURITY
DoD	DEPARTMENT OF DEFENSE
ESS	EXTENDED SERVICE SET
GFE	GOVERNMENT FURNISHED EQUIPMENT
GMR	GROUND MOBILE RADIO
IETF	INTERNET ENGINEERING TASK FORCE
JTRS	JOINT TACTICAL RADIO SYSTEM
LPD	LOW PROBABILITY OF DETECTION
LPI	LOW PROBABILITY OF INTERCEPT
MANET	MOBILE AD HOC NETWORKS
MGV	MANNED GROUND VEHICLES
MIMO	MULTIPLE INPUT MULTIPLE OUTPUT
MIO	MARITIME INTERDICTION OPERATIONS
NOC	NETWORK OPERATIONS CENTER
OFDM	ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING
OSD	OFFICE OF THE SECRETARY OF DEFENSE
OSI	OPEN SYSTEM INTERCONNECTION
P2P	POINT-TO-POINT
PDA	PERSONAL DIGITAL ASSISTANT
PCMCIA	PERSONAL COMPUTER MEMORY CARD INTERNATIONAL ASSOCIATION
PHY	PHYSICAL LAYER
PMP	POINT-TO-MULTIPOINT

PRNET	PACKET RADIO NETWORK
QOS	QUALITY OF SERVICE
SA	SITUATIONAL AWARENESS
SATCOM	SATTELITE COMMUNICATION
SDR	SOFTWARE DEFINED RADIO
SURAN	SURVIVABLE RADIO NETWORK
TNT	TACTICAL NETWORK TOPOLOGY
UAS	UNMANNED AERIAL SYSTEMS
USSOCOM	UNITED STATES SPECIAL OPERATIONS COMMAND
UWB	ULTRA WIDE BAND
VLAN	VIRTUAL LOCAL AREA NETWORK
VPN	VIRTUAL PRIVATE NETWORK
WN	WIRELESS NODE
WNW	WIDEBAND NETWORKING WAVEFORM

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I.   INTRODUCTION

A.   BACKGROUND

The past decades have witnessed advances in computing and communication technologies. Faster, smaller and more reliable devices enable communications with rapid, efficient information dissemination between mobile users. In a tactical environment, units need a network that can support information sharing and collaboration on the move. Due to the harsh nature of the tactical environment (e.g., weather and terrain features), tactical networking challenges include low *bandwidth*, very high *latency*, and poor reliability.

Battlefield networks do not have a fixed network infrastructure. Mobile ad hoc networks do not depend on any kind of established infrastructure; therefore, they can be deployed in austere and dynamic tactical environments. The Mobile Ad hoc Networks' (*MANET)* flexibility makes it an attractive *networking* option for *tactical* operations. Mobile ad hoc networks have several advantages over traditional wireless networks. These advantages are on demand setup, fault tolerance, node's increased mobility, self-organizing connectivity, adaptive, self-managing, scalable ad hoc network routing. MANETs are useful in tactical operations such as MIO (Maritime Interdiction Operations) and United States Special Operations Command (USSOCOM) operations where rapid deployment of a communication network is needed.

MANETs inherit the traditional problems of wireless and mobile communications, such as bandwidth optimization, power control, and transmission quality enhancement [1]. The objective of the Control based Mobile Ad hoc Networking (CBMANET) program by Defense Advanced Research Projects Agency (DARPA) was to "provide robust communications networks to ensure that the application of force is not limited by the flow of information" [2]. Many problems with MANET were expected to be solved by the integration of CBMANET into military radio systems. After completing the development and

integration of CBMANET into military radio systems, DARPA executed field experiments and military demonstrations. The review of the final field experiment results in 2009, DARPA put a halt on the program.

B.   BENEFIT OF STUDY

The objective for this master's thesis is to review a series of key performance indicators of integrating CBMANET into tactical networks. It accomplishes this by analyzing CBMANET field experiment results to evaluate how CBMANET can increase the bandwidth and efficiency of a wireless network in a tactical environment. In other words, this thesis analyses the feasibility of using CBMANET in tactical wireless networks, and investigates scenarios regarding where CBMANET can be used with the current state of tactical networking experimentation.

The benefit that this study yields is a competent understanding of CBMANET concepts. Current network capabilities are addressed while developing a control based mobile ad hoc network. Overall, this research envisions that CBMANET will significantly increase the efficiency of current MANET.

C.   TACTICAL WIRELESS NETWORKS

Today's tactical networks are a complex network centric system, where sensor systems, unmanned vehicle systems, and distributed systems of mobile units, transfer and analyze data while they are moving [3]. Tactical wireless networks should provide reliable, survivable, secure and seamless communications capabilities to the tactical edge. A tactical wireless network often experiences connectivity problems for a variety of reasons including limited or no fixed network infrastructure, dynamically maneuvering units, challenging transmission conditions, and faulty network and collaboration schemes [4].

Recent military conflicts have proven the importance and operational need of delivering real-time services to warfighters in theater. Tactical wireless

networks support a wide range of products and tactical services, such as passing command and control orders, information exchange (e.g., biometric results, annotated video, voice, and map graphics), and surveillance and sensing data (e.g., radar, biometric, and biochemical sensors) [5]. As the demand for higher bandwidth real-time tactical services increase, more bandwidth efficient tactical network solutions must be achieved [6]. Because of the mission requirements and battlefield circumstances, there needs to be minimal impact on bandwidth usage and availability.

Like all communication systems, tactical wireless networks are also subject to hostile attacks. It becomes important to protect the data due to the sensitive nature of the data sent by military applications over tactical wireless networks. Tactical wireless networks should support secure communications to meet its performance and functional objectives. The constrained resources on mobile nodes, limits security solutions due to their processing requirements, power consumption, speed and routing overhead.

Another key characteristic of tactical wireless network is survivability due to the possible effects on mission accomplishment [7]. Network survivability is the capability of a system to provide essential services, in a timely manner, under dynamic topology, attacks or failures [8]. Ensuring authenticity, accuracy, availability under a full range of threats faced by these mobile nodes is difficult because tactical wireless networks have limited resources (e.g., battery duration and limited bandwidth), use noisy communications channels, and are susceptible to attack [9]. The goal of survivability is to establish and maintain network connectivity among dynamic groups of users, such as dynamically formed coalition teams employed to accomplish a mission [7].

Tactical wireless networks are generally considered unreliable due to the potential of packet loss. Depending on battlefield conditions, much of the data sent will not be received, be received late, or received out of order. Providing reliable networking services in tactical wireless networks is very challenging due to high mobility and unstable wireless environment. Tactical wireless networks

require high reliability because messages conveyed in tactical networks contain critical information. Network coding and erasure coding can increase reliability in multicast communications [10]. Multiple Input Multiple Output (MIMO) communication links are common in tactical wireless networks for bandwidth efficiency and fading. Multicasting builds multiple paths from senders to receivers. Higher redundancy results in higher reliability because packets can be delivered even in the presence of unreliable links (e.g., intermittent outages). By taking advantage of network coding, MIMO communication, and the use of multicasting, it is possible to increase reliability.

Tactical wireless networks perform significantly below the levels of connectivity, latency, and throughput that are achievable on a wired network. Tactical networks must comply with the anticipated characteristics associated with Command and Control (C2) applications in order to meet the required current and future information needs of the warfighters. Also, C2 applications should be developed comparable to the tactical network on which they effectively operate [11].

1.   MANET

The idea of ad hoc networking started with DARPA's Packet Radio Network (PRNet) project in 1972. PRNET was the first implementation of wireless ad hoc networks with limited mobile nodes. PRNET presents a distributed architecture consisting of network of broadcast radios with minimum central control. It was encouraged by the efficiency of the packet switching technology in bandwidth sharing, *store and forward* routing, and its possible applications in mobile wireless environment [12]. DARPA developed Survivable Radio Network (SURAN) to address main issues in PRNET in the early 1980s. The main objectives were to a develop network algorithm to support a network that provided the ability to scale to tens of thousand of the nodes and resist security attacks, as well as use small, low-cost, low-power radios that could support sophisticated packet radio protocols [13]. The Internet Engineering Task

Force (IETF) established a working group named MANET that has worked in the field of ad hoc networks since 1997. The purpose of this working group is to "standardize IP routing protocol functionality suitable for wireless routing application within both static and dynamic topologies" [14]. Mobile ad hoc networks are usually unplanned, self-organizing networks composed of mobile nodes that utilize mesh networking principles for interconnectivity [15].

Tomorrow demands military forces to be mobile, communicating, agile, and situation-aware. These forces will consist of diverse branches of soldiers operating with manned and unmanned platforms and sensors. All these network centric platforms must be capable of performing well in a wireless, mobile, highly dynamic networking environment. MANET is one of the most important technologies that supports future battlefield scenarios. MANET offers several significant advantages to a military force. A MANET's ability to self-form and self-manage eliminates the need for central management of network links, thus reducing support personnel and equipment requirements. MANET enables mobile military forces to share data more easily and achieve greater situational awareness than a non-networked force.

MANET's distinctive benefits provide tactical users great opportunities together with some challenges. It experiences the problems of both traditional wireless and mobile networks. MANET has five distinct limitations including:

1. Connectivity: MANETs experience connectivity difficulties due to environmental factors. Like all wireless networks, they are naturally impacted by environmental factors (e.g., man-made, natural terrain features, other RF devices) that can impact network connectivity. The network topology may change randomly and rapidly at unpredictable times as mobile nodes join, leave, or fail over time. Dynamic topology also affects connectivity. Identity and location of the nodes for naming and addressing issue is a problem in MANETs due to the dynamic topology [16].

2. Bandwidth: Wireless links have relatively lower capacity than hardwired links. The effects of multiple access, fading, noise, and interference conditions also decrease the maximum transmission rate available by communication devices. The nodes on MANETs

5

will have varying capabilities thereby varying capacity links. When MANET users demand services like multimedia applications (e.g., videoconferencing, streaming media) and collaborative networking applications, it is possible that demands will frequently approach or exceed network capacity.

3. Resources: many of the devices (i.e., nodes) that operate in MANETs have limited battery and data storage capacity. Some or all of the nodes in a MANET may depend on exhaustible batteries for power supply. For this reason, energy conservation is important for the nodes. The mobile nodes usually have limited data storage and low computational capabilities. The limited data storage capacity of one node may not meet the demands of multimedia applications.

4. Scalability: Connectivity must be highly scalable, encompassing thousands of nodes or more in order to create ubiquitous networking in the battlespace. A substantial challenge concerning the integration of mobile nodes is the accomplishment of scalable and efficient mobile ad hoc routing. Scalability limits the network due to the additional workload associated with the routing nodes.

5. 5) Security: MANETs are prone to physical security threats. Mobility implies higher security risks such as in peer-to-peer network architectures or a shared wireless medium accessible to both legitimate network users and malicious attackers. There is always a possibility of eavesdropping, spoofing, and denial-of-service attacks. Link security techniques must be applied within these networks to reduce security threats [16].

Along with those challenges, the issue of end-to-end latency should not be ignored. As MANET gets larger and denser with an increasing number of end-to-end hops, the latency and jitter experienced by packets will be high for real-time applications. Although the objective MANET strives to reduce latency as much as possible, MANET also must be tolerant to intermittent high latency and even multiple node disconnects and re-entries to the network.

Figure 1. shows the three problems MANET suffers from: the unsuitability of ISO-layered modularization; high protocol overhead; and the absence of adaptive cross-layer network resource allocation [17]. Consequently, these

connectivity, bandwidth, resource, scalability, security limitations and latency are significant MANET constraints and are the key drivers of current and future network technology and design research on MANETs.
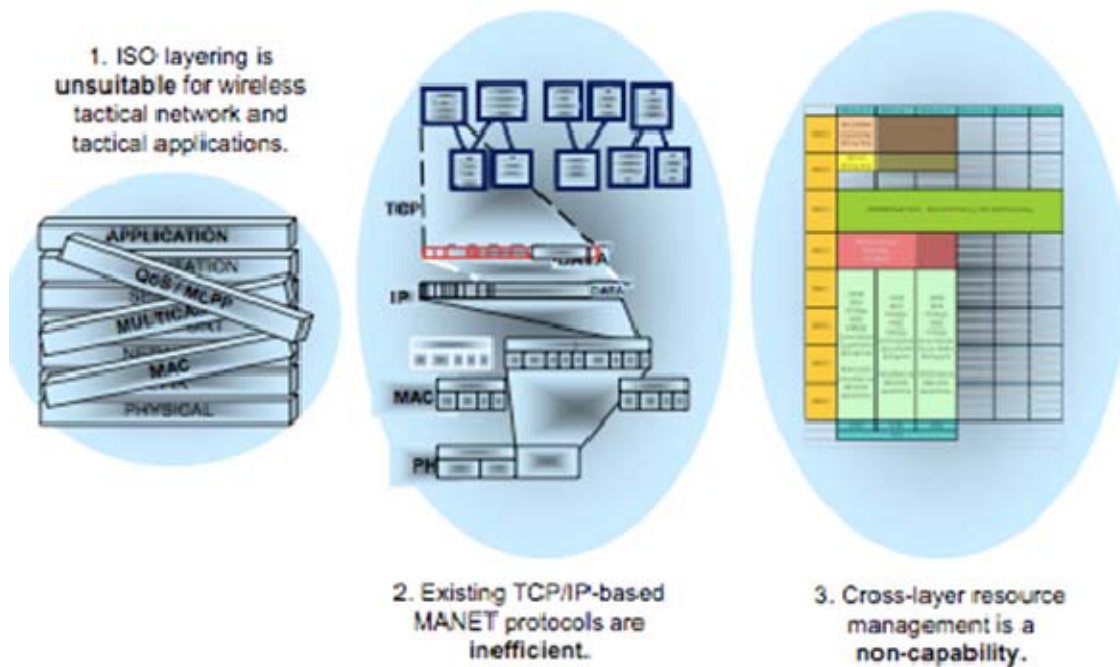
Figure 1.   Challenges of MANET From [17]

2.   CBMANET

While flexibility makes MANET an attractive networking option for tactical operations, classic networking approaches adapt poorly to the rapid network changes inherent in a battlespace environment and achieve only a fraction of the potential performance.   The objective of DARPA's CBMANET contract is to research, design, develop, and evaluate a new protocol stack for MANET [18]. Another prime objective of the CBMANET program has been to capitalize on recent theoretical advances in distributed adaptive network control to solve the distributed resource allocation problem in tactical MANET.   The adjective

"Control-Based" is used to describe a potential for improving the performance of MANET system architecture using distributed adaptive control mechanisms.

The CBMANET program developed an adaptive networking capability that dramatically improved performance and reduced critical communication failures in complex communication networks. Conventional MANET are composed of interdependent nodes that are based on interdependent system layers. Each MANET node exposes tens to hundreds of configurable parameters that must be continuously adapted due to variable tactical factors such as mission profile, phase, force structure, enemy activity, and environmental conditions. The complexity of this high-dimensional, adaptive, constrained, distributed network configuration problem is overwhelming to human operators and designers, and has root causes in the historically wire-line-oriented networking paradigms [19].

This research takes on the ambitious goal of exploring a novel protocol stack that provides integrated optimization and control of all network layers simultaneously. Key technical challenges are scalable design, stability, and convergence. These challenges are especially difficult in a distributed setting with partial and uncertain information, high communications overhead, and high probability of link failure. To address this problem, the CBMANET program developed a network stack from first principles with specific attention to support for Department of Defense (DoD) applications such as multicast voice video, chat, file transfer, and situation awareness by exploiting recent optimization-theoretic breakthroughs, recent information-theoretic breakthroughs, and comprehensive cross-layer design [20].

C.   THESIS OUTLINE

Chapter II familiarizes the reader with the general tactical wireless networking and the wireless networking technologies. Chapter III provides the field experiment results of CBMANET; those results are examined, discussed and analyzed. Finally, Chapter IV discusses the research findings and outlines potential areas that CBMANET can be use with the current state.

II.   TACTICAL NETWORK TESTBED (TNT) TOPOLOGY

A.   GENERAL

Encouraged by the need to have ubiquitous connectivity, there has been impressive growth in the field of wireless networking in the past two decades. A wireless network is a network that connects communication technologies by using electromagnetic radiation to move data from one node to another. A variety of devices and services use different methods to accomplish information sharing among wireless networks by using radio signals. Each service has a different set of features, and each uses a slightly different technology. The four most widely used wireless technologies are Wi-Fi, WiMAX, and 3G and emerging 4G cellular services. The data rates for wireless technologies and the speed can be seen in Figure 2. whereby 4G and WiMAX have the fastest speed.
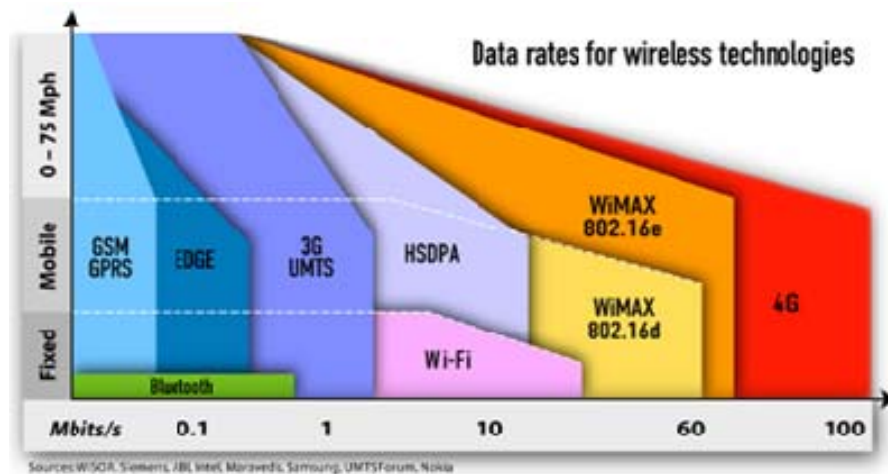

Figure 2.   Data Rates for Wireless Technologies

B.   OVERVIEW

The idea of improving the interfaces between the Department of Defense, other government agencies, the private sector, and the academic community to integrate and operate emerging technologies that could enhance the military's

information systems drives some major research objectives. With the sponsorship of USSOCOM, Office of the Secretary of Defense (OSD), and more recently the Department of Homeland Security (DHS) S&T Programs, a group of researchers from the Naval Postgraduate School (NPS) started the interagency experimentation program named TNT in 2002.

"In the core of TNT experimentation is a unique testbed, which enables sustainability and evolution of the experimentation process. It provides for the adaptation and integration processes between people, networks, sensors, and unmanned systems. It enables plug-and-play tactical-on-the-move sensor-unmanned systems networking capabilities combined with global reachback to remote expert/command sites and augmentation by rapid integration of applied research services."[21]. Simulated battlefield scenarios are conducted to develop, evaluate and improve warfighter communications, real time video and biometrics utilizing unmanned air, ground and sea vehicles.

The TNT program has adapted and evolved as technologies, standards and other necessities changed. TNT experimentation facilitates easy plug-and-play participation, rapid prototyping, and integration of multiple technologies (e.g., networking communications systems, Unmanned Aerial Systems (UASs), and sensors) into the different segments and layers that constitute TNT testbed.

A Network Operations Center (NOC) on the NPS campus acts as the hub for linking the various off-site participants as shown schematically in Figure 3. The linkages are made using an ever-changing set of Virtual Private Network (VPN) tunnels on top of a fixed TNT wireless (802.16) tactical backbone between NPS and Camp Roberts/Fort Hunter Liggett (slightly over 100 miles distance), various on-site wireless networks (see Figure 4. it illustrates one of the self-forming mesh segments of the TNT with UASs and different combined applications), and satellite links or the commercial IP cloud to permit other remote site connections to the TNT infrastructure.
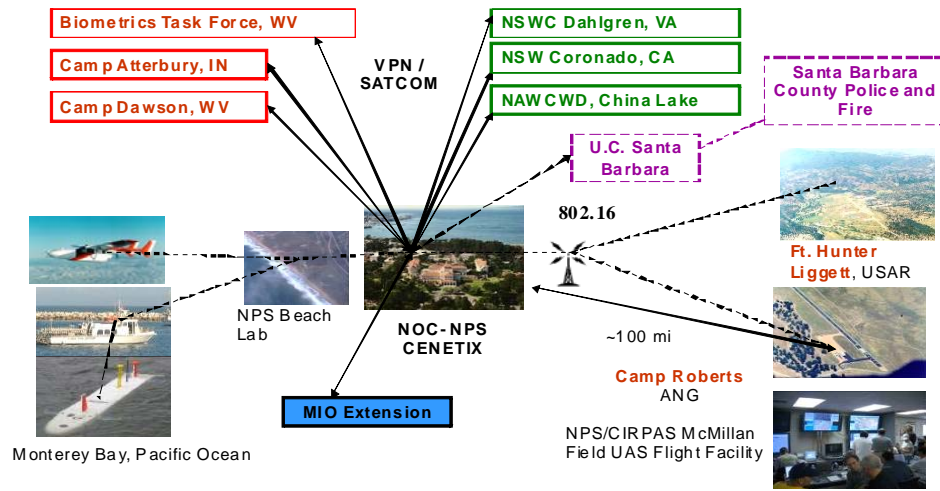
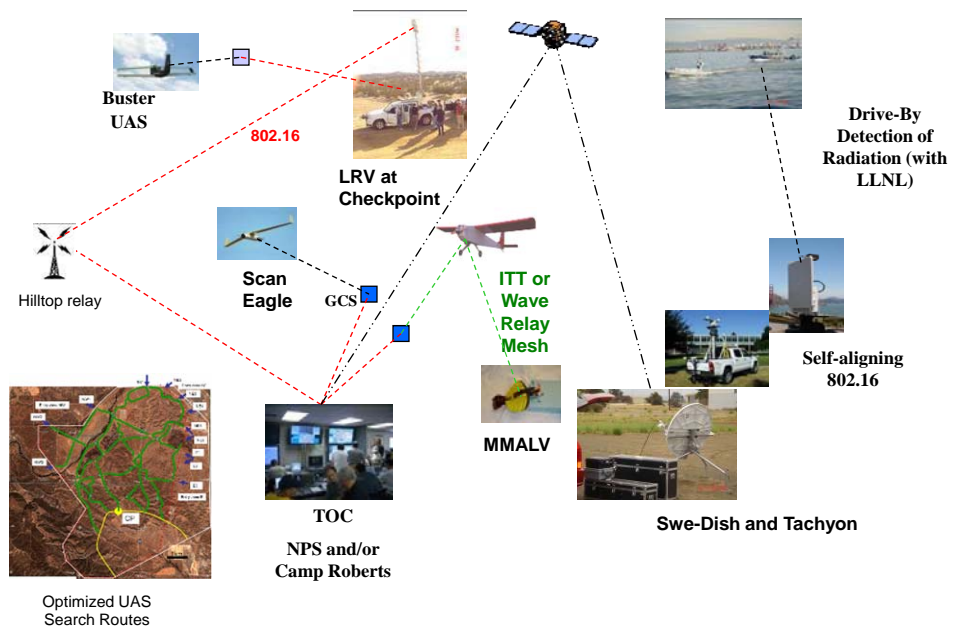Figure 3.   Plug-and-Play Testbed with Global Reachback

Figure 4.   Typical Self-Forming Mobile Mesh Segments of TNT Testbed

C. WIRELESS TACTICAL NETWORK CAPABILITIES

Key to the data exchange in tactical field is the development of scalable wireless networks supporting end user mobility. This is consistent with current networking capabilities with respect to large-scale mobile network capabilities and protocols. However, future architectures and capabilities should allow for more flexible and robust capabilities.

While in the tactical mobile edge, the mobile nodes reside on small, highly mobile platforms such as soldier networks, unmanned aerial systems, manned aerial systems and manned ground systems. These communications platforms comprising the tactical edge networks support Satellite Communications (SATCOM) on a limited basis and more likely will rely on wireless communications [22]. The necessary communication links could be accomplished by using a variety of solutions: Wi-Fi, WiMAX, UWB, Wireless Mesh Networks which offer easy deployment and flexibility in order to implement distributed information networks and to exchange information between mobile military units. Characteristics (such as data rate) change from one specific solution to another. There are however a number of prerequisites that is required by applications and users: including reliability, availability and security.

1. Wireless Fidelity (Wi-Fi)

The Institute of Electrical & Electronics Engineers (IEEE) 802.11 standard was released in 1997 and many amendments have been developed since then. Wi-Fi is an application of the IEEE 802.11 standard. Wi-Fi technology was designed to prevent the high installation and maintenance costs caused by additions, deletions and changes experienced in wired LAN infrastructure. Additionally, various IEEE 802.11 standards are being developed in order to increase the performance of Wi-Fi networks and to provide users with greater flexibility.

Wi-Fi is often used in point-to-multipoint (PMP) environments to allow extended network connectivity (e.g., private/backbone network, Internet) of multiple portable devices such as laptops, PDAs, handhelds, and mobile cellular phones. Wi-Fi also allows point-to-point (P2P) connectivity, which enables devices to directly connect and communicate to each other. The IEEE 802.11 standard defines two modes, which are depicted in Figure 5.

- Infrastructure mode: The wireless network consists of at least one access point (AP) connected to the wired network and a set of wireless nodes (WN). This configuration is called a Basic Service Set (BSS). Extended Service Set (ESS) is a set of two or more BSSs.

- Ad hoc mode: This configuration is called Independent Basic Service Set (IBSS) and is useful for establishing a network where wireless infrastructure does not exist or where services are not required.
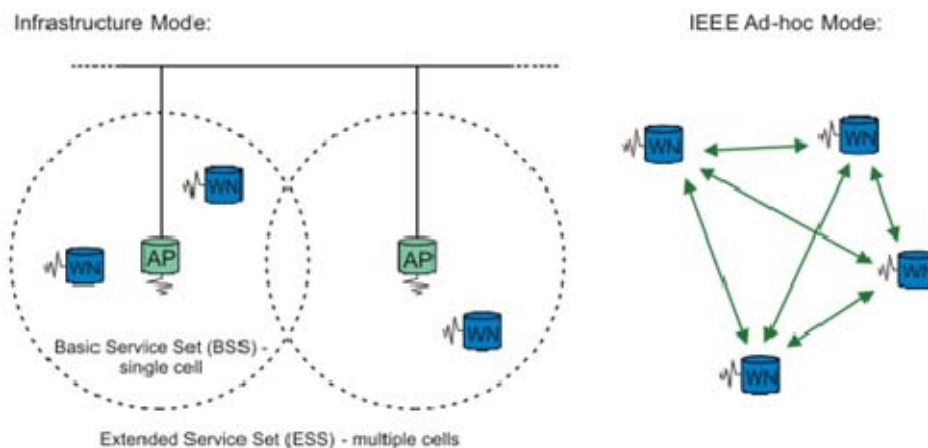
Figure 5.   Infrastructure and Ad Hoc Mode of IEEE 802.11

Wi-Fi can be used in conjunction with other emerging wireless technologies, such as WiMAX and Wireless Mesh Networking, to extend the coverage area of networks, and to provide high-speed data and services to mobile devices. Wi-Fi also can be used to create a Wireless Mesh Network: a decentralized, reliable, resilient, and relatively inexpensive solution for areas of weak or destroyed network infrastructure. This technology is beneficial for the creation of higher performance ad hoc networks.

2.   OFDM/802.16 (WiMAX)

Orthogonal Frequency Division Multiplexing (OFDM) is an FDM modulation technique for transmitting large amounts of digital data over a radio wave. OFDM works by splitting the radio signal into multiple smaller sub-signals that are transmitted simultaneously at different frequencies to the receiver: multiple carrier waves take the place of and carry the data of one large wave. The power spectral density of OFDM, multiple carriers dividing the data across the available spectrum, depicted in Figure 6.
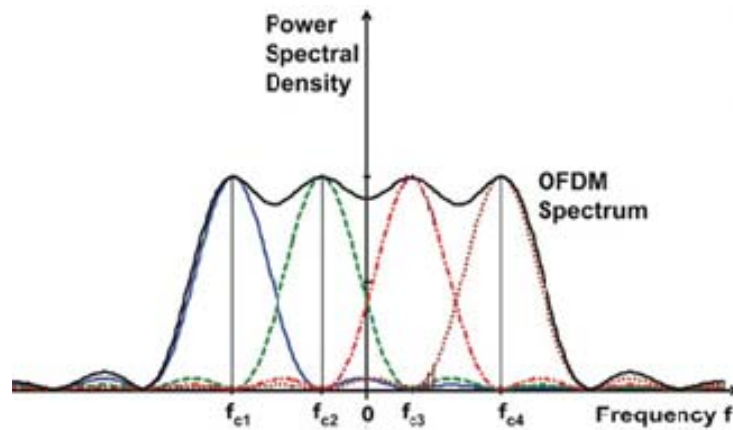
Figure 6.   The Power Spectral Density of OFDM

The primary advantage of OFDM is that the multiple carrier waves overlap; that provides a very efficient use of the frequency bandwidth by packing more data into the bandwidth compared to what can be achieved with a single larger carrier wave spread across the same spectrum. The other benefits of OFDM are resiliency to RF interference and lower multi-path distortion. Also, OFDM eliminates crosstalk inbetween the sub-channels. Among others, the IEEE 802.11a and 802.11g Wi-Fi standards use OFDM as well as IEEE 802.16 because of the inherent advantages in high-speed communication. The IEEE 802.16 network also support mesh topology, where Subscriber Stations (SS) are able to communicate among themselves without the need of a Base Station (BS). A typical IEEE 802.16 Network is shown in Figure 7.
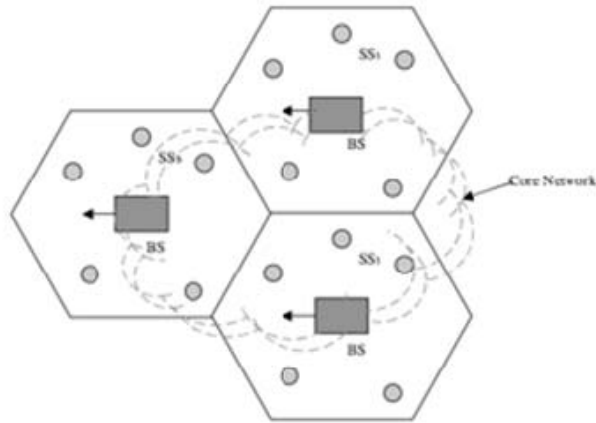
Figure 7.   A Typical IEEE 802.16 Network

Worldwide Interoperability for Microwave Access (WiMAX) is a wireless communication system that allows communication devices to connect to high-speed data networks by using radio waves with data rates over 75 Mbps for each radio channel.   WiMAX can be used for both fixed and mobile broadband wireless access. WiMAX offer exponentially greater range and throughput than Wi-Fi. It also offers better quality of service (QoS) and security.

The IEEE 802.16 standard provides for two main distinct uses of this technology, point-to-point (PTP) and point-to-multipoint (PMP) as shown in Figure 8. PTP connections may be independent from all other systems or networks. A PMP system allows a radio system to provide services to multiple users.
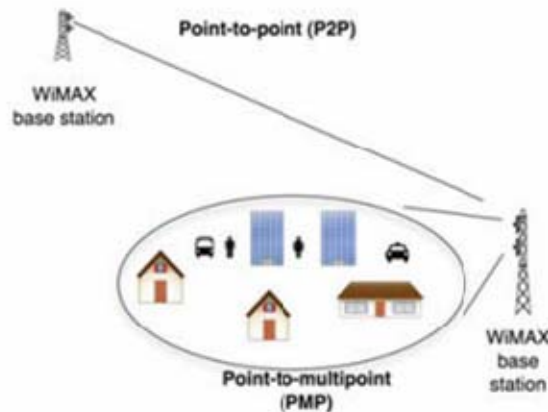
Figure 8.   Point-to-Point and Point-to-Multipoint Configurations

IEEE 802.16 supports ATM, IPv4, IPv6, Ethernet and Virtual Local Area Network (VLAN) services. Mobile WiMAX was originally defined by the 802.16e-2005 amendment. It allows mobile user in the coverage areas to access high speed services through their IEEE 802.16/WiMAX enabled mobile handheld device by enhancing the OFDMA (Orthogonal Frequency Division Multiplexing Access). The current 802.16 version is IEEE 802.16-2009 amended by IEEE 802.16j-2009. It is expected that with the IEEE 802.16m update will offer up to one Gbit/s fixed speeds [23].

3.   Ultra Wide Band (UWB)

In the United States, the Federal Communications Commission (FCC) regulates the use of the frequency spectrum by stipulating the permitted bandwidth of the signal for a given radio system. FCC has mandated that UWB radio transmissions operate in the range from 3.1 GHz up to 10.6 GHz at a limited transmit power of –41dBm/MHz [24].

UWB technology provides a cost-effective, power-efficient, high bandwidth solution for short-range communications. UWB complements other wireless network technologies such as Wi-Fi, WiMAX, and cellular networks. UWB also

offers covert Low Probability of Detection / Low Probability of Intercept (LPD/LPI) communications that are robust against multipath fading and interference, and precise ranging capabilities.

UWB has the ability to propagate through solid materials by means of lower frequency. Lower frequency waves have the characteristic of being able to pass through walls because the length of the wave is longer than the material that it is penetrates. This ability makes UWB an intriguing technology in terms of battlefield communications. It offers a communication channel to convey data in harsh indoor and urban environments such as shipboard communications on a non-network enabled (e.g., a ship being searched for contraband during a MIO), and also communication in urban operations.

Integrating the UWB link into the peer-to-peer wireless mesh networks will help to fulfill the vision of ubiquitous wireless access in a fully-connected battlespace. Table 1. provides a high-level comparison between Wi-Fi, WiMAX, Ultra Wideband and Wireless Mesh technologies.

Table 1.   High-Level Comparison of Wireless Technologies After [25]

Technology	Wi-Fi	WiMAX	Ultra Wideband (UWB)	Wireless Mesh
Features	• WLANs (e.g., indoor, office, campus environment) • PMP mode, with each client connected to an AP; P2P mode, with each mobile user connected directly to each other • Can operate in line-of-sight and non line-of-sight situations • Supports fixed, portable and mobile	• Metropolitan area networks (MAN) • PMP and P2P capabilities • Can operate in line-of-sight and non line-of-sight situations • Supports fixed, portable, and mobile communications • Typically used as a backhaul to connect multiple Wi-Fi hotspots to external networks • With adaptive	• Wireless personal area network (WPAN) • Severe broadcast power restrictions • High data rate streams, Cost-effective, power-efficient, high bandwidth solution for short range communications • Can propagate through solid materials • Has the	• Type of wireless ad hoc network • Peer-to-peer communications, with each mobile user acting as a client and AP • Self-organizing, self healing, and auto-configuring • Typically uses wireless technologies in the unlicensed band, including 802.11, 802.16, cellular technologies or combinations of more than one type

Technology	Wi-Fi	WiMAX	Ultra Wideband (UWB)	Wireless Mesh
	communications	features, WiMAX has the ability to adapt to various channel conditions and communication scenarios.	capability to meet QoS constraints and adopt to environmental conditions.	

D. COMMERCIAL WIRELESS MESH NETWORKING SYSTEMS

1. ITT MESH

ITT Mesh is a commercial-off-the-shelf-technology (COTS) that uses wireless network cards with an internal amplifier. The Personal Computer Memory Card International Association (PCMCIA) wireless card provides scalable, high performance mobile ad hoc networking for military use. By using the wireless modem card, shown in Figure 9. , up to 6 Mbps of data transmission is available for streaming video, audio, images and maps [26]. Its key features are high bandwidth, connectivity for on-the-move operations, no need for network managers, instant-on operations.

Figure 9.   ITT WMC—An Ad Hoc Networking Modem Card From [26]

The ITT Mesh has the advantages of being self-forming and self-healing with full connectivity between nodes. As a consequence of not having a central authority, each node pulls data through a separate channel that causes overall

bandwidth to be divided by each node. In addition to the bandwidth issue, the ITT Mesh network is fragile and prone to interruption by competing frequency use as well as antenna pointing and masking problems.

2. WAVE RELAY™

Wave Relay™ is an adaptable wireless communication system that allows integrating large numbers of meshed nodes into a network to form the infrastructure. Wave Relay™ provides a dynamic and seamless multi-hop networking solution for military needs. The Wave Relay™ Mobile Ad Hoc Networking System is also available in a Man Portable, providing a wearable wireless connectivity solution for users on the move. (see Figure 10.)

Figure 10.   The Wave Relay™ Mobile Ad Hoc Networking System is Available in a Man Portable, Providing a Wearable Wireless Connectivity Solution for Users on the Move. From [27]

The Wave Relay™ is designed to maintain peer-to-peer routes and connectivity while all nodes are continuously in motion. The system detects changes in connectivity and, using routing protocol, adjusts the pathways in order to maintain the most efficient route between them. In addition, scalability allows nodes to participate in the mesh; thereby, increasing interconnectivity and performance. Increasing routing options leads to better connectivity and higher network capacity and efficient use of network resources.

Wave Relay™'s ability to deliver the mesh to the end users results in multiple advantages ideal for military operations. In a military operation, all of the mobile assets need to remain continuously connected to enable arbitrary peer-to-peer communications. The Wave Relay™ system is design for environments where channel conditions are continuously fluctuating and fading, and where connectivity is continuously changing as nodes move around obstructions which create fast RF transitions.

The Wave Relay™ architecture runs on OSI Layer 2 (the data link layer) of networking stack, allowing plug and play. Any device that runs over Layer 2 can instantly be connected to the network. Wave Relay™ can be directly connected to an existing Ethernet switch allowing the network to bridge an entire wired network into the system. The advantages of that are seamless connectivity, and easy setup and deployment.

The Wave Relay™ software can be used to build a custom mesh networking product or to integrate Wave Relay™'s dynamic routing capability into an existing embedded product. The Wave Relay™ software architecture shown in Figure 11. Wave Relay™ with its peer-to-peer topology, high fault tolerance, high-performance connectivity, and efficient bandwidth distribution characteristics, is capable of delivering voice, video, and other demanding applications in a constantly changing wireless network topology.
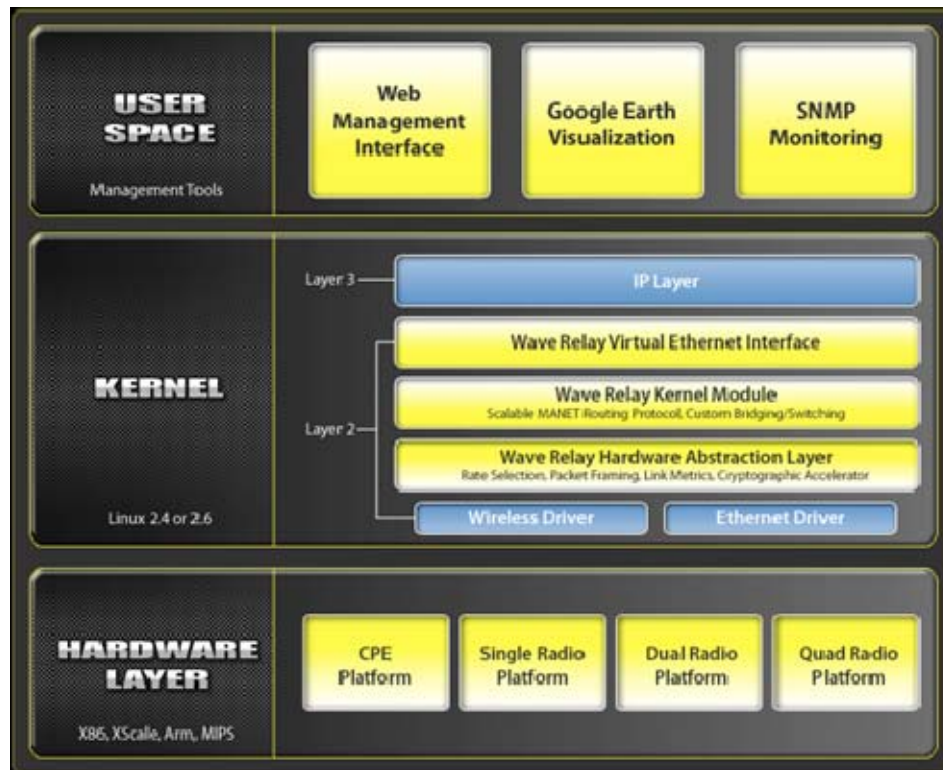
Figure 11.   Wave Relay Software Architecture From [27]

3.   The Joint Tactical Radio System (JTRS)

Recognizing the opportunities that software-defined radio (SDR) technology brings, the U.S. Department of Defense created the Joint Tactical Radio System (JTRS) program to provide warfighters with a flexible standards-based approach to meet their diverse communications needs with "future-proof" capabilities.

JTRS, Ground Mobile Radios (GMR), is a software-programmable radio system providing secure, reliable, multi-channel voice, data, imagery and video communications for mobile military users.   The system delivers networked communications on-the-move at the tactical field supporting information sharing and combat readiness between service branches (e.g., Army and Navy).

The plan for JTRS is to develop a family of affordable, high-capacity tactical radios to provide both line-of-sight and beyond-line-of-sight C4I

capabilities to the warfighters. JTRS is not a one-size-fits-all system; however, it is envisioned as a family of radios that are interoperable, affordable and scalable. A single JTRS radio with multiple waveforms can replace many separate radios, simplifying maintenance.

A waveform is the entire set of radio and/or communications functions that occur from the user input to the radio frequency output and vice versa. JTRS waveform implementation consists of a Waveform Application Code, Radio Set Devices and Radio System Applications. There are nine JTRS waveforms.

- Wideband Networking Waveform (WNW)
- Soldier Radio Waveform (SRW)
- Joint Airborne Networking–Tactical Edge (JAN-TE)
- Mobile User Objective System (MUOS)
- SINCGARS
- Link-16
- EPLRS
- High Frequency (HF)
- UHF SATCOM

The JTRS program will develop a flexible hardware baseline that can integrate functional modules and software as required to meet any operational task. One of the objectives of JTRS program is to network the radios in a MANET. MANET protocols are designed to handle these wireless environments. MANET aims to enable communication between military users using a single software defined radio to emulate any of several current military radio systems. Each JTRS networking waveform employs a MANET protocol tuned to its peculiar environment. These protocols interact with the IP layers in the radios to hide the network mobility and dynamics from the external commercial-based networking equipment to facilitate interoperability.

Through (1) the Wideband Networking Waveform (WNW), (2) routing and retransmission via the use of MANET capabilities, and (3) multi-channel

attributes, JTRS GMR offers a number of unique capabilities that provide the warfighter with an enhanced operational capacity never before realized.
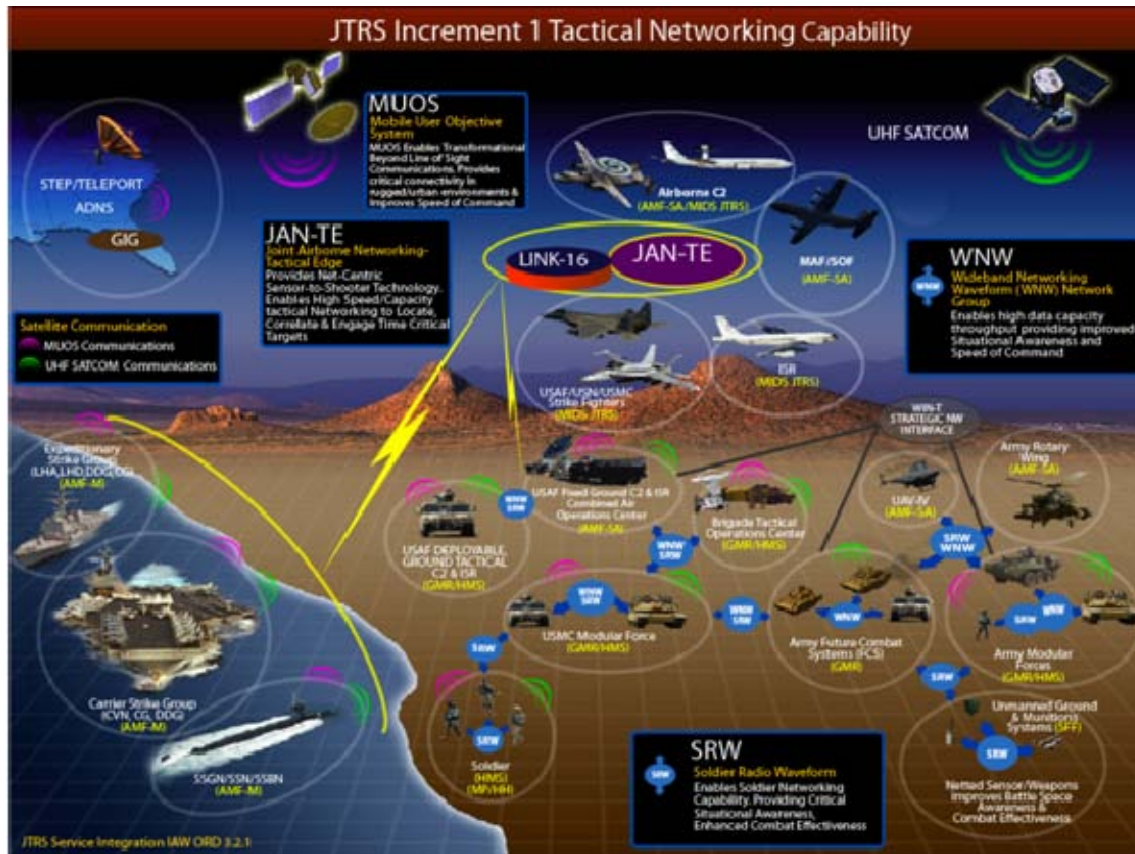
Figure 12.   JTRS Increment 1 Tactical Networking Capability

E.   SUMMARY

Clearly, wireless communications will continue to develop because of the ever increasing demand for mobility and networking connectivity in military operations.   Features of wireless networks will enable them to become a dominant solution for tactical networks.   Other emerging networking capabilities hold promise for future tactical networking solutions.   CBMANET is one such solution and is addressed in the next chapter.

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III.   ANALYSIS OF CONTROL BASED MODEL

A.   CAPACITY OF NETWORKS

Wireless mesh networks consist of a number of nodes as shown in Figure 13. These nodes are equipped with a routing functionality and communicate with each other through radio links. Their role is to collect the data sent by other nodes and to forward that data through a single or multi-hop transmission toward other nodes. An example of such networks is mobile ad hoc networks. A MANET is an autonomous collection of mobile nodes that does not have fixed infrastructure and any centralized control.
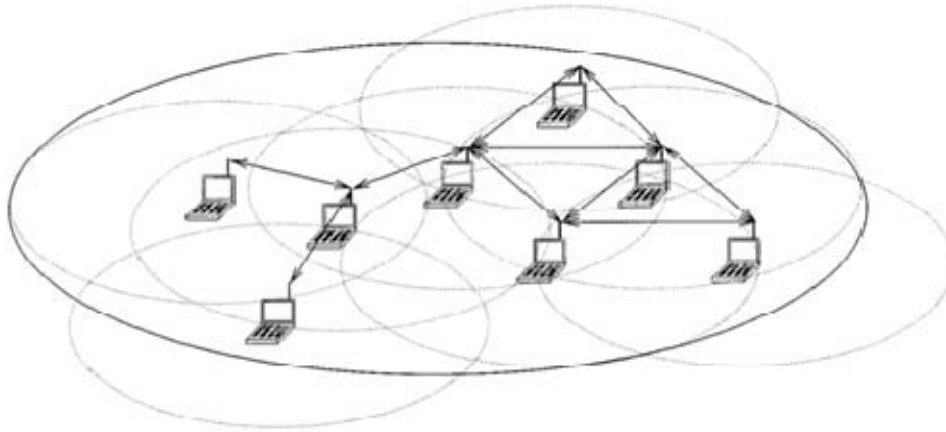
Figure 13.   A Wireless Mesh Network Architecture

The performance of those networks is then evaluated, specifically the data flow quality of service (QoS) that it is feasible. The total capacity of those networks grows with the area that they cover due to spatial re-use of the spectrum: nodes sufficiently far apart can transmit simultaneously; however, ad hoc routing requires that nodes cooperate to forward each others' packets through the network. The throughput available to each single node is limited not only by the raw channel capacity, but also by the forwarding load imposed by other nodes. That affects the utilization of the benefits of a mobile ad hoc

network. Fundamentally, the reason for the constriction in capacity is the need for every node in the network to share whatever portion of the channel it is utilizing with other nodes in its neighborhood.

The capacity is defined as the maximum bandwidth that can be allocated to each node. The objective of studies in capacity is to increase the number of nodes while ensuring a better quality of service and improving the efficiency or obtaining more bandwidth. The capacity of a wireless mesh network is one of the most important criteria of quality of service, hence optimizing usage of capacity is appropriate. This metric is directly linked to the available bandwidth to each node of the network, or to the whole network.

Shannon's Law on channel capacity dictates that the potential data rate of wireless networks (C) (in bits/s) is directly proportional to the bandwidth (B) (in Hz) of the channel and the logarithm of the signal-to-noise ratio (SNR). The Shannon formula is given by Equation 3.1.

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \qquad (3.1)$$

Multicasting plays a significant role for data transmission in bandwidth scarce MANETs. In many applications, multicast data transfer is more predominant than unicast data transfer. In implementation of MANETs in the military environment, multicast has the advantage due to wide use, potential applications, and the need for group communications. Because of the transmission bandwidth limitations in wireless ad hoc networks, multicast can significantly improve the network performance.

MIMO is a method where multiple data streams are transmitted over a channel simultaneously. MIMO offers improvement in wireless network capacity in a multipath environment. To optimize the capacity of ad hoc channels, MIMO concepts and techniques can be applied to multiple links between node clusters. The use of multiple antennas at both the receiver and transmitter, forming a MIMO system, has been shown to increase the spectral efficiency. MIMO

provides the greater capacity and spectral efficiency needed to deliver video, chat, and other information sources across mobile nodes to improve SA. Even when one path fades, there is still a high probability that the other paths support the signal getting through. The advantage is that the reliability of signal reception is increased. MIMO signal processing techniques can also be used to reduce transmit power while maintaining a reliable radio link.

In their seminal paper [28], Gupta and Kumar started an interest in understanding the fundamental capacity of wireless ad hoc networks. Several techniques have been developed in order to improve the capacity of wireless ad hoc networks. The idea of network coding to enhance throughput utilization was first proposed by Ahlswede et. al.[29] in the context multicast communication. Network coding has been investigated as a potential tool for the design of communication networks in order to enable the data transmission rate to expand the capacity limit. His work has motivated a large number of researchers to investigate the impact of network coding for improving the throughput capacity of wireless ad hoc networks [30]. Researches try to show whether network coding has practical benefits and can substantially improve wireless throughput.

B.   NETWORK CODING (CONCERTO)

Network coding is a paradigm that allows packets to be combined in-network, unlike traditional store-and-forward routing. Network coding encodes the messages received at intermediate nodes prior to forwarding them to following next-hop neighbors. The advantage of network coding can be seen from the canonical example in Figure 14. Ahlswede et al [29] showed that coding within a network allows a source to multicast information at a rate approaching the smallest cut between the source and any receiver.
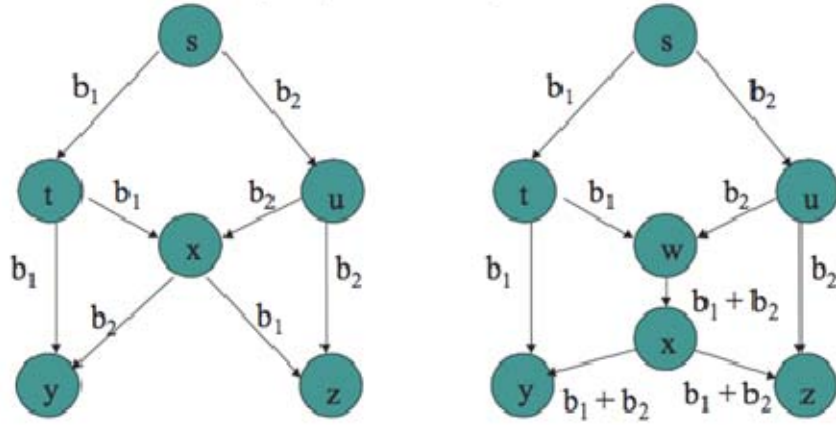
Figure 14.   Canonical Example [29]

The usefulness of network coding in a practical MANET setting is a subject of debate as its effectiveness is known to be topologically sensitive. However, the very nature of military ground operations indicates a strong use of multicast as orders and SA dissemination is required to various mobile units operating in challenging communications environments. Since theory indicates network coding favors multicast situations, it would be prudent to examine its performance when applied to ground military operations. A project, named Control Over Network Coding for Enhanced Radio Transport Optimization (CONCERTO) was supported by the DARPA CBMANET program. CONCERTO was a multi-institution project (BAE Systems, CalTech, Cornell, MIT, Penn State (PI:T. La Porta), Stow Research, UIUC, UMass) The aim was to demonstrate that network coding along with careful cross layer design provides a significant performance improvement [31].

The main source of delay in network coding is due to the need for the destinations to collect enough packets to decode a generation of packets. Latency will ultimately determine network coding's applicability in real-time communication systems with stringent delay constraints.

C.   CBMANET EXPERIMENT HISTORY

CBMANET was being developed in two incremental phases. The first phase of this program planned to last approximately 18 months long. It started at June 2006 completed at December 2007. Phase 1 ended up with a simulation demonstration of the system. In Phase 1, performers delivered a high-fidelity model of their software that meets or exceeds the threshold program metrics. Performers also delivered that software, with installation support. The modeling and simulation demonstration fully exercised CBMANET protocol performance with an offered load of representative of tactical applications.

The second phase of this program took 12 months long and ended up with a field demonstration of the system. Second phase started in March 2008 and completed in July 2009. In phase 2, performers delivered an integrated hardware solution combining their software, a specified GFE physical layer (PHY) board, and the computing platform of their choice. Phase 2 ended up with a field demonstration of the CBMANET system implementation on actual hardware. At a minimum, the Phase 2 simulation and field demonstrations must meet the threshold metrics. The field demonstration will fully exercise CBMANET protocol performance as described. Phase 2 will involve additional improvements to the Phase 1 system, integrating the Phase 1 system with the Government-specified physical layer, and then running experiments both in laboratory and field settings.

Table 2. shows threshold objectives for each phase for the CBMANET program. As the table implies, requirements are prioritized and metrics for each phase are determined depending on this prioritization. Summary of CBMANET phases and context are shown in Table 3.

Table 2.   CBMANET Program Metrics From [32]

Program Metrics	Baseline	Phase 1 (Month 18) Go / No-Go Criteria (Threshold)	Phase 2 (Month 30) Go / No-Go Criteria (Threshold)
Principal Metric: Minimum bandwidth required by the CBMANET as a percentage of what was required by the baseline network.	100%	40% (Simulation Threshold) + analysis showing how any unfulfilled Phase 2 performance improvements are expected to be achieved	10% (Simulation and Field Test)
Conditioned on: Comparable network effectiveness	Network meets requirements of the offered load and/or the network supports the network load as effectively as the baseline using a comparative utility-based methodology		
Number of network nodes	30	30 (Simulation)	30 (Hardware) 30/50/130 (Simulation)
Interoperability with legacy networks demonstrated	Yes	No	Yes
Network is robust to the addition of a new application	Yes	Yes	Yes
Network initialization time	<6 min.	<6 min.	<3 min.
Node entry time	<30 sec.	<30 sec.	<15 sec.
Detect node exit time	<10 sec.	<10 sec.	<10 sec.

Table 3.   Summary of CBMANET Phases and Context After [33]

CBMANET Phase 1 (6/06 –12/07)	CBMANET Phase 2 (3/08 –7/09)
Reduce MANET bandwidth while providing comparable performance	Increase carried load while providing comparable performance
"Application Utility" defines "comparable performance"	"Application Utility" defines "comparable performance"
NRL Baseline protocol suite	SOCOM Baseline protocol suite
The modeling and simulation demonstration	A field demonstration of the CBMANET system implementation on actual hardware
Emulated radios, emulated applications and emulated scenario	Real tactical radios, real applications and real scenarios

During the Phase 2, five field experiments were conducted. The large-scale experiments were held at Hayes Field during June 2009 with 2 aircraft, 2 trucks, and 31 dismounts. The work effectively ended in September 2009. Only the latest field experiment results for the Field Experiment 4 are evaluated in the next section.

D.   FIELD EXPERIMENT 4

The concept behind the CBMANET program metrics is that a network can be assessed by determining how efficiently it uses wireless network resources, as determined by assessing the bandwidth required to meet the requirements of a given offered load. Accordingly, a control-based network ought to meet the requirements of a given offered load as well as the baseline network, but the control-based network ought to require less bandwidth (an order of magnitude less bandwidth by the end of Phase 2). Phase 2 involved additional improvements to the Phase 1 system, integrating the Phase 1 system with the Government-specified physical layer, and then running experiments both in laboratory and field settings.

The objective of this evaluation criterion is to ensure that CBMANET innovations prove worthwhile. Factors to be evaluated include vulnerabilities, robustness to failure, and support for encrypted traffic. The goal is to provide the same network effectiveness while using only 10% of the bandwidth used by the government baseline model [34]. Even though in [34] the term "network efficiency" is not described clearly, one can intuitively consider it as the amount of pure data and total network traffic in a specific time period. As compared to the government provided model, a control based model, or CBMANET, increases the performance of the network and saves nine-tenths of the bandwidth. This allows the users in the network to utilize that saved bandwidth to benefit other applications or implement complex applications that are likely to be basic requirements for future military communications.

The goal of the CBMANET program is very difficult to accomplish. In order to track, evaluate, and modify the program's process and prevent any deviation from the goal, researchers attempt to accurately define and continuously assess metrics. The main metrics for the CBMANET program are network effectiveness, latency, data throughput, and power consumption [32].

In order to evaluate the effectiveness of a CBMANET, DoD delivered an integrated software/hardware solution for field demonstrations and evaluation. Although the proposed effort achieved some quantitative and qualitative success criteria, after determining satisfactory progress was not achieved in the program metrics at Phase 2, DARPA discontinued funding of the program.

Figure 15. depicts elements of Phase 2 experimentation. ground tactical scenario operation field and locations of units. 20 dismounted nodes partook:

- Node 1-3, 23, 24:   Command Post (Green)
- Nodes 4-8:   Objective Alpha (Red)
- Nodes 9-13:   Objective Bravo (Blue)
- Nodes 14-20:   Sensors (Purple)

Two mobile nodes, nodes 21, 22, were used in the scenarios. Tactical applications such as SA, chat, video and file transfer were used in scenario involving ground forces. All Load 1, 2, 3 used in this experiment defined as providing end user utility for SA, chat, file transfer and video traffic types to different number of destinations nodes. All comparisons made within the loads' success according to the loads they are utilized. There were six phases associated with the overall scenario that was presented for testing and evaluating. The six phases of the scenarios including movements and loadings are delineated in Table 4.
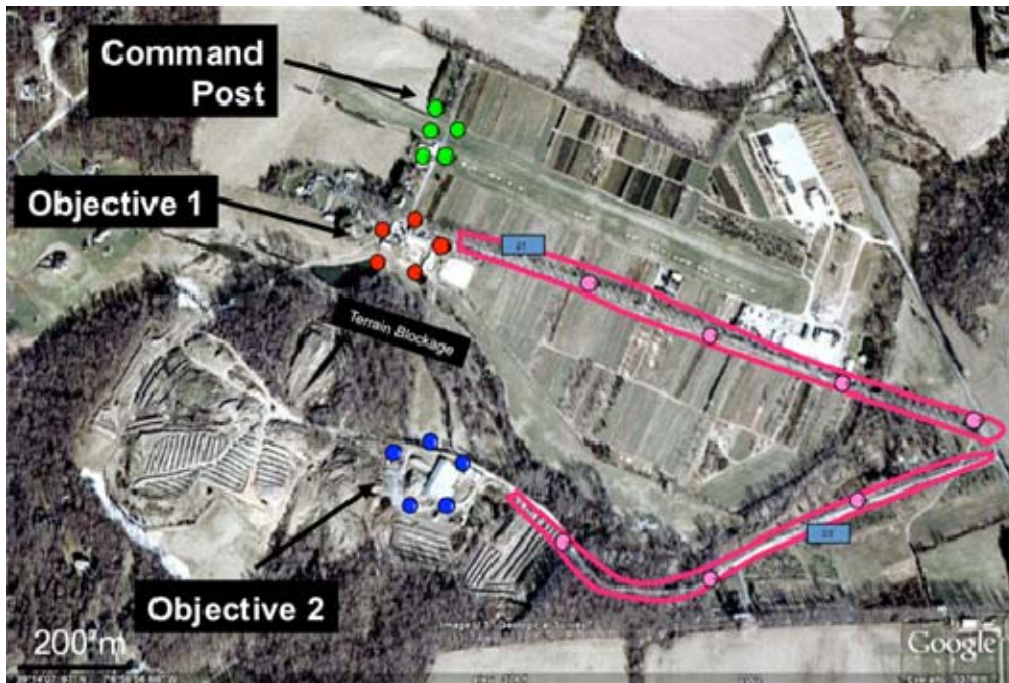
Figure 15.   Field Experiment 4: Ground Tactical Scenario From [35]

Table 4.   Phase Scenarios, Movements and Loads From [35]

Scenario	Movement	Nodes	Loads
Alpha	Collect at Landing Zone (LZ)	All nodes at command post	All loads for 5 min each
Bravo	Deployment	Dismounts and sentries deployed	Load 1
Charlie	Attack on Objective 1	•Nodes 4-8 Attack Objective 1 •Nodes 21/22 on patrol	All loads for 10 minutes each
Delta	Attack Objective 2	•Nodes 9-13 Attack Objective 2 •Nodes 21/22 on patrol	All loads for 10 minutes each
Echo	Recover dismounts	Dismounts and sentries deployed	All loads for 5 min each
Foxtrot	Collect at Landing Zone (LZ)	All nodes at command post	Load 1

The following is a description of the field test results. Figure 16. shows the ground scenario variable video performance—video utility diagram. In Alpha phase, both models have 100 percent utility. In Bravo Phase, the CBMANET

provides slightly more utility with 97 percent. In the other phases, however, the CBMANET shows apparent superiority against the baseline model. In these phases, the CBMANET utility only deteriorates slightly, on the other hand, the baseline utility decreases as low as 33 percent and becomes effectively unusable. Figure 17. illustrates the total MANET traffic diagram of the ground scenarios.
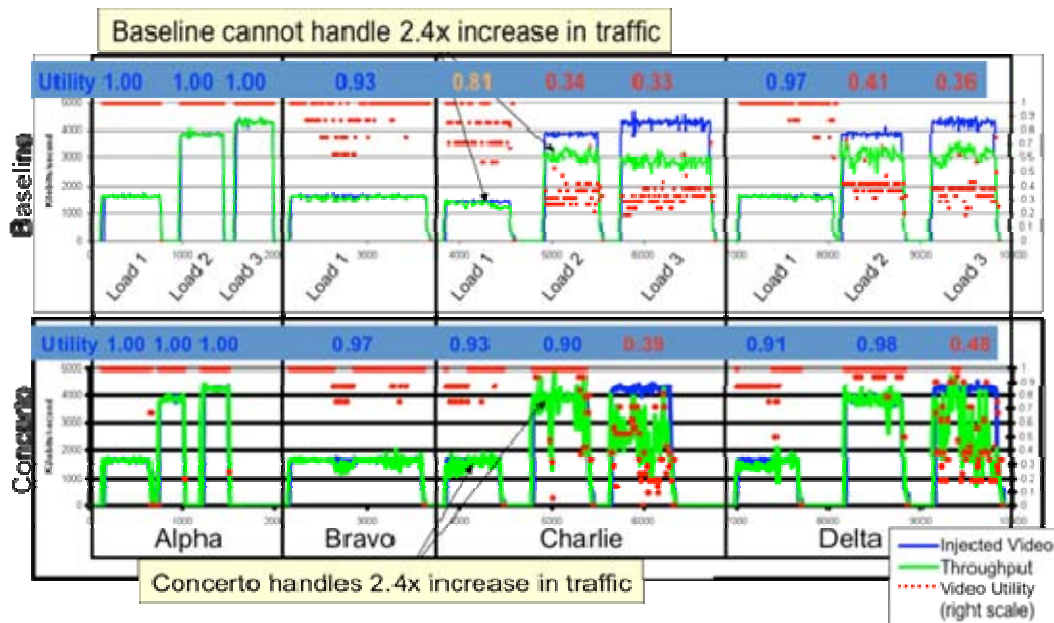

Figure 16.   Ground Tactical Scenario—Video Utility From [35]
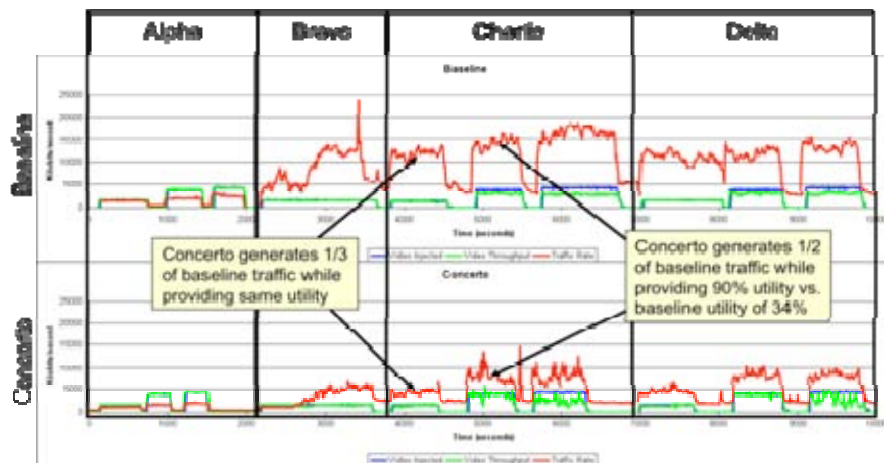

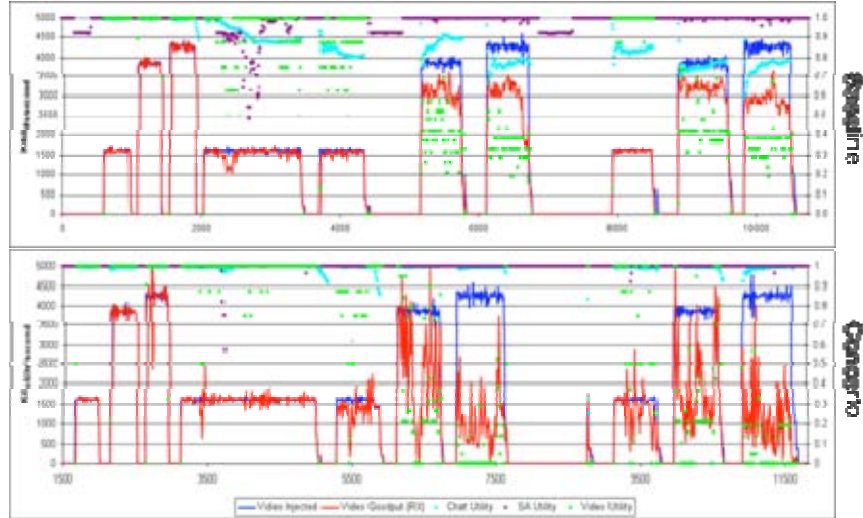Figure 17.   Ground Tactical Scenario—Total MANET Traffic From [35]

Figure 18.   Air Tactical Scenario From [35]

Comparing the results between the baseline and Concerto 6-Node Video/Chat/SA results from Table 5. and Table 6. it is easy to determine that Concerto has high latency in all situations. When the actual injected video stream rate increases, latency gets higher.   Although Concerto has better goodput (i.e., application level throughput), latency can increase up to 10,000 msec. For example, two nodes communicating through six intermediate hops generated a 10 seconds delay.

Table 5.   Baseline 6-Node Video/Chat/SA From [35]

Injected Rate	Goodput (Kilobits/seconds)			
	Min	Ave	Max	Std. Dev.
200	182.9	196.2	210.7	8.5
400	191.0	299.5	348.2	39.1
600	0.0	254.0	442.8	158.8
800	233.7	344.4	442.6	56.9

Injected Rate	Latency (milliseconds)			
	Min	Ave	Max	Std. Dev.
200	615.5	690.8	762.6	43.4
400	787.1	943.0	1311.8	124.4
600	965.5	1150.8	1298.7	89.3
800	1142.2	1348.0	1554.5	130.0

Table 6.   Concerto 6-Node Video/Chat/SA From [35]

	Goodput (Kilobits/seconds)			
Injected Rate	Min	Ave	Max	Std. Dev.
400	77.9	396.9	611.5	104.7
800	693.5	813.7	942.1	58.7
1200	47.1	145.1	599.6	105.7

	Latency (milliseconds)			
Injected Rate	Min	Ave	Max	Std. Dev.
400	1321.5	3025.6	7818.6	1740.4
800	1404.1	3073.0	6844.0	1460.7
1200	7912.0	9772.5	10176.5	419.1

Concerto radios consume more power than baseline radios due to their processors. While baseline radios can work with 533 MHz XScale ARM processors (Gateworks Avila) Concerto radios requires more powerful processors such as 2 GHz Intel Core 2 Duos (Aaeon Gene) or 800 MHz Marvell ARM processor (Gateworks Pismo). Field experiment 4 showed that measured power usages on the 6-node linear engineering scenario with Video, Chat and SA traffic are

- Gateworks Pismo power draw: 6.5-8.5 watts (Baseline Radio)
- Gateworks Avila power draw: 4.6-7.0 watts (Concerto Radio)

The results show that CBMANET performed better than the baseline model in some metrics. In some cases, it improves performance over the baseline, and it generates less traffic. According to these metrics, CBMANET have the capacity to be used in MANETs in *latency-tolerant* networks, but it still needs to be improved.

IV.   CONCLUSION

Battery life in wireless communication systems has been one of the major limitations.   Power consumption should be optimized in order to maximize the total battery life of mobile ad hoc networks.   Minimum energy usage in networking can effect important benefits (e.g., longer battery life and mitigate interference) in the digital battlefield, especially in sensor networks. CBMANETs have inherent significant technical challenges because of the many constraints related such as unreliability of wireless links, limited energy consumption and dynamic network topology. This introduces a trade-off between link maintenance in highly unreliable networks and power conservation for users with little battery power. CBMANET uses considerably more power because the network coding requires considerable processing for each packet at each node. This requires much more power than what is necessary for normal retransmissions. CBMANET was originally built on quad processor 3.0GHz Pentiums with 16 GB of RAM. The code was nearly unusable on a 750 MHz ARM processor with 256 MB of RAM. Those facts imply that the computers in the radios must be upgraded to accommodate CBMANET. The new computers used approximately twice as much power as was previously used in battlefield computing devices.

Latency refers to any of several kinds of delays typically incurred in the processing of network data. Field experiments showed that the delay imposed by network coding was very large.   End-to-end latency is of paramount importance in a number of real-time applications such as interactive video (e.g., video teleconferencing), VOIP, and real-time imaging. Latency experienced by packets will be prohibitively high for existing and emerging real-time applications on the battlefield. In order for these applications to seamlessly extend to military MANETs, comparable latency needs to be provided.

Another challenge in interconnecting CBMANETs with backbone legacy networks is the lack of compatibility between protocols.   CBMANET is

incompatible with any other protocol. A rough work-around proposed to solve this problem is to disable network coding. Disabling network coding means giving up all the benefits of it. Hence, integration within the IP architecture will re-emerge as a problem.

CBMANET was successful for non-interactive streaming video (e.g., YouTube); however, this type of transmission has little military utility. The other applications tested were chat, FTP, and blue-force tracking. Those showed slight differences between CBMANET and the baseline. CBMANET showed virtually no improvement over the baseline protocol in Field Experiment 4 with the exception of broadcasting YouTube videos. CBMANET was inefficient for voice and interactive video and did little for other traffic types that are commonly used. There is a significant possibility that CBMANET would have provided improved delivery of non-interactive, non-time critical streaming video. In summary, CBMANET makes little difference except for transmission types that the military does not use or seldomly uses, and it makes two major traffic types—voice and video-teleconferencing—unusable because of latency.

The experiment examined the strengths and weaknesses of CBMANET and tried to answer the question—"Can CBMANET deliver enough capacity to support services required by warfighters in tactical environments?". Warfighters on the battlefield require robust information technology for secure, reliable, real-time access to mission-critical information. Real-time applications such as voice communications, video-teleconferencing are highly latency sensitive. The results suggest that delay-tolerant applications (e.g., some sensor network applications such as battlefield surveillance) can take advantage of CBMANET to increase the throughput capacity of such networks.

In the *tactical operations* context, rapid deployment and self-organization of networks are required. MANETs have the capacity and quality of service required for tactical wireless networks. In terms of network capacity, lifetime, and latency, MANETs need to be improved. It is important to consider all of these issues and trade-offs for such networks such as delay-throughput when

analyzing these systems. Since network resources of MANET are limited due to the multiple users sharing the same spectrum, and power resources of mobile nodes is constrained due to the energy-limited batteries, the scalability issue is one of the main research topics in developing MANET routing algorithms. It is well known that wireless communications consume significant amounts of battery energy, and the limited battery lifetime imposes a constraint on network performance; therefore, energy efficient operations are critical to prolong the network lifetime.

Adaptive networking will become essential in MANETs. This approach enables the network to dynamically allocate shared resources as changes occur in the networking environment. Tactical wireless networks should be designed to interact with fast changing events in the battlefield.

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